Train Control to Reduce Delays upon Service Disturbances at Railway Junctions

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Abstract: Train delay is one of the most important indexes to evaluate the service quality of the railway. Because of the interactions of movement among trains, a delayed train may conflict with trains scheduled on other lines at junction area. Train that loses conflict may be forced to stop or slow down because of restrictive signals, which consequently leads to the loss of run-time and probably enlarges more delays. This paper proposes a time-saving train control method to recover delays as soon as possible. In the proposed method, golden section search is adopted to identify the optimal train speed at the expected time of restrictive signal aspect upgrades, which enables the train to depart from the conflicting area as soon as possible. A heuristic method is then developed to attain the advisory train speed profile assisting drivers in train control. Simulation study indicates that the proposed method enables the train to recover delays as soon as possible in case of disturbances at railway junctions, in comparison with the traditional maximum traction strategy and the green wave strategy.

Key Words: Railway transportation; Train control; Heuristic method; Railway junctions; Delay recovery

1 Introduction

In China mainline railway system, characterized by the high-volume traffic and short headway, a severe disturbance of a single train may cause massive disturbances in the whole railway network. For example, once a train is delayed at junction area, it may conflict with trains scheduled on other lines. The train that loses conflict is usually forced to stop or slow down before the conflicting point because of restrictive signals. In many cases, the result is a remarkable loss of run-time which may enlarge train delays. This paper addresses the problem of time-saving train control under the three-aspect fixed block signaling system in case of service disturbances, to minimize the time that train departs from conflicting area and therefore recover delays as soon as possible.

Previous studies on train control mostly focus on automatic train control [1-2] and energy-efficient train control [3-5]. There are a few studies address time-saving train control. The maximum traction strategy [6], which controls the train speed as close to the maximum speed as possible, always leads to the minimal run-time in normal situation. However, in case of service disturbances occurred at junction area, train that loses conflict adopting the maximum traction strategy may be forced to stop or slow down before the conflicting point. Consequently, the loss of time and energy caused by stop or slow down may enlarge train delays. The maximum traction strategy is therefore not necessarily suit to the problem discussed in this study.

With the broad availability of communication and position technology, the time of signal changes could be predicted and conveyed to trains. Based on this information, green wave strategy [7] is developed for daily operation of Dutch railway network. Green wave strategy means anticipating slow down the train in front of conflicting area to make the train face only green signal aspects. Computational experiments turn out that the green wave strategy is an effective way to reduce energy consumption. However, it does not achieve significant delay reduction in comparison with maximum traction strategy [8].

In the problem discussed in this paper, the train that loses the conflict may face red signal aspect in front of conflicting area. Assuming the time of red signal aspect upgrades is known, train position and speed at this critical time is the most important factor impacting on the time when the train departs from conflicting area. In maximum traction strategy, train position is nearest to the conflicting area at the critical time but the speed is decreased because of signaling constraints. On the contrary, in green wave strategy, train speed is able to reach the maximum speed while train position is farthest to the conflicting area at the critical time.

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Therefore, they are not necessary to minimize the time used by the train for its departing from the conflicting area. Both studies [7] and [8] point out that there is an optimal approaching speed at the critical time and it generates minimal train delays in conflicting area. However, they do not point out how to identify the optimal approaching speed.

This study proposes a method to identify the optimal approaching speed at the critical time that enable the train to depart from the conflicting area as soon as possible, and then develops a heuristic method to attain advisory speed profile to assist the driver in train control. Simulation studies comparing the train delays and energy consumptions of the optimal approaching strategy, maximum traction strategy and green wave strategy are conducted to show the effectiveness of the proposed method.

2 Problem description

China mainline railways mostly adopt the fixed-block signaling system. Inter-station section is divided into a number of block sections separated by signals. For safety reasons, the signals impose a dynamic speed limitation on train movement to guarantee a minimal headway between consecutive trains. For three-aspect fixed block signaling system, a signal aspect may be green, yellow or red. A green signal implies that the next two block sections are empty. A yellow signal aspect means that only the subsequent block section is empty and it requires the train to slow down. A red signal aspect indicates the subsequent block section is occupied by another train and the train must stop in front of the signal post showing red. A detailed description of China railway signaling system and traffic control regulations can be found in study [6].

Figure 1 shows the interactions of movement among trains at a junction in case of service disturbances. Train A is running from block section 2 to block section 8. Train B is scheduled on another line running from block section 1 to block section 9. The block section 5 is shared by Train A and B. In scenario (a), train B is punctual and train A is not being influenced by restrictive signal aspects. In scenario (b), train B is delayed which causes a conflict of train A and B at the shared block section 5. Train A is only allowed to enter the block section 5 if the signal aspect is either green or yellow, which means train B have already crossed the junction area. The signal post of the first shared block section is called critical signal post. The section from the critical signal post to where the train driving with the maximum traction strategy recovers its speed to the maximum speed is called conflicting area.

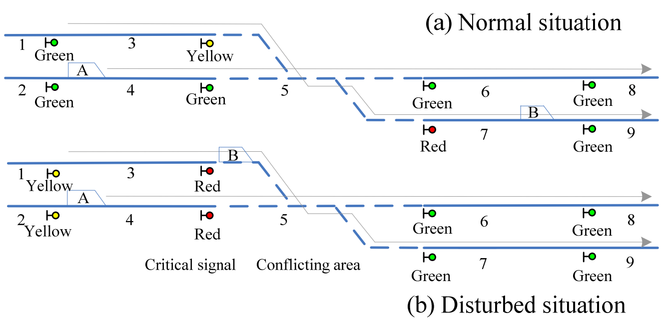

Fig. 1 An example to illustrate interactions of movement among trains at a junction

In scenario (b), the delay may be propagated from train B to train A. This study aims to attain an advisory speed profile of train A assisting the driver to reduce the delay propagation. At time t_a when the aspect of critical signal post turns from red to green, train state (speed and location) is constrained by the speed limit curve imposed by signaling system [9]. Among all possible train states, the closer to the critical signal post the position, the higher the speed, the train is prone to cross the conflicting area earlier. Therefore, train time-saving control may involve the following three control strategies, maximum traction strategy, green wave strategy and optimal approaching strategy.

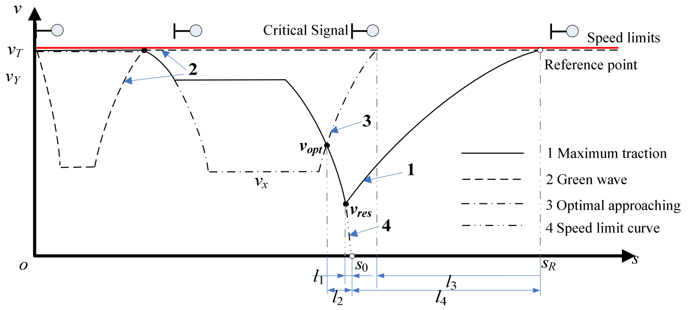

Fig. 2 Train speed-distance curves with three typical control strategies

The maximum traction strategy is to drive the train as closer to critical signal post as possible at time t_a, and the train speed profile is illustrated by curve 1 in figure 2. To achieve this objective, train adopts the maximum traction so that the train speed is always close to the speed limits. Let v_{res} be the train speed at time t_a. The later the aspect of critical signal post upgrades, the lower the train speed v_{res} is. In the case that $v_{res}>0$, the train must not be closer to the critical signal post than the minimal braking distance needed for the train to stop. Especially, $v_{res}=0$ implies that the train is forced to stop in front of critical signal post at time t_a.

The green wave strategy is to enable the train to operate at maximum speed v_T at time t_a. The train speed profile driving with green wave strategy is illustrated by curve 2 in figure 2. To achieve this objective, the train should slow down in advance to arrive at the critical signal post after its aspect turns to green. The distance between the train and the critical signal post at t_a must be bigger than the length of the block section in front of critical signal post.

As illustrated by curve 3 in figure 2, the optimal approaching strategy is to drive the train approaching critical signal at time t_a with the optimal speed $v_{opt}\in(v_{res}, v_T)$, which minimizes the time that the train departs from conflicting area. Studies [6] and [8] develop the train control method for maximum traction strategy and green wave strategy, respectively. This paper aims to propose a method to attain the advisory train speed profile of optimal approaching strategy. At the end, simulation studies are conducted to compare the train run-time and energy consumptions of the aforementioned three strategies.

3 Train control with the optimal approaching speed

For each possible approaching speed, the time when the train departs from the conflicting area can be computed by train motion equations [6]. Thus enumeration method is a feasible way to identify the optimal approaching speed. However, the computing efficiency of a simple enumeration method is hard to meet the requirement of on-line calculation. Therefore, this section first discusses the relationship between the approaching speed and the time when the train departs from the conflicting area, to propose an intelligent searching method to identify the optimal approaching speed.

3.1 Theoretical analyses

Theoretical method is able to compute the train run-time with a given section and control strategy. However, simplifications, such as regarding the train as a mass point and considering the train movement as a uniformly accelerated motion, are usually assumed to obtain the results within a reasonable computation time. Although these simplifications may cause that the results deviate from the real one, theoretical method is still a useful way to examine the preliminary relationship between the approaching speed and the time when the train departs from the conflicting area.

Let v_{gi} be the train approaching speed at time t_a, the time t when the train departs from the conflicting area is computed as follows,

$$t = t_a + t_{acc}(v_{gi} \to v_T) + l_3 / v_T \tag{1}$$

Where, $t_{acc}(v_{gi}\to v_T)$ denotes run-time for the train which is accelerated from v_{gi} to v_T, and l_3 defined in figure 2 denotes the traveling distance of the train with target speed. To simplify calculations, train movement is regarded as a uniformly accelerated motion. Train acceleration and deceleration rates are denoted by $a_1$and a_2, respectively. By introducing auxiliary variables l_1, l_2 and l_4 defined in figure 2, following equations based on physical movement equations are obtained to calculate the time t.

$$t_{acc}(v_{gi} \to v_T) = (v_T - v_{gi}) / a_1 \quad (2)$$

$$l_1 = v_{res}^2 / (2a_2) \quad (3)$$

$$l_2 = v_{gi}^2 / (2a_2) \quad (4)$$

$$l_3 = l_2 + l_4 - (v_T^2 - v_{gi}^2) / (2a_1) \quad (5)$$

$$l_4 = (v_T^2 - v_{res}^2) / (2a_1) - l_1 \quad (6)$$

By substituting l_3 and t_{acc} from equations (2)-(6) into (1), time t is obtained:

$$t = t_a + (v_T - v_{gi}) / a_1 + (v_{gi}^2 - v_{res}^2)(a_1 + a_2) / (2a_1 a_2 v_T) \quad (7)$$

Regarding v_{gi} as the variable, equation (7) can be transformed to a linear quadratic equation:

$$t = t_a + v_T / a_1 - (a_1 + a_2) v_{res}^2 / (2a_1 a_2 v_T) - a_2 v_T / (2a_1(a_1 + a_2)) + (\sqrt{(a_1 + a_2) / (2a_1 a_2 v_T)} v_{gi} - 1 / 2a_1 \sqrt{(a_1 + a_2) / (2a_1 a_2 v_T)})^2 \quad (8)$$

According to the equation (8), it could be deduced that the optimal approaching speed v_{opt} is $a_2 v_T/(a_1+a_2)$. In such case, the time t is minimized:

$$t^{\min} = t_a + v_T / a_1 - (a_1 + a_2) v_{res}^2 / (2a_1 a_2 v_T) - a_2 v_T / (2a_1(a_1 + a_2)) \quad (9)$$

It can also be deduced that the relationship between the approaching speed and time t can be depicted by a single-peak function. In case of $v_{gi}>a_2 v_T/(a_1+a_2)$ and $v_{gi}<a_2 v_T/(a_1+a_2)$, time t is monotonically decreases and increases, respectively, when the v_{gi} moves from v_{res} to v_T.

3.2 Simulation studies

Assuming train acceleration and deceleration rates are constant in braking and motoring process, the relationship between the approaching speed and the time when the train departs from the conflicting area is discussed in section 3.1. However, the acceleration and deceleration rates may be changed in real-life train braking and motoring. In order to achieve more realistic results, this section further examines the relationship between approaching speed and the time when the train departs from the conflicting area by simulation studies.

A general-purposed train movement simulator [10] is adopted to calculate the time for the train departing from the conflicting area with different approaching speed. The railway network for simulations is illustrated by figure 3. The railway network consists of two intersected lines. Train A (total weight: 360t, train length: 377m) is running from the original station S_a to the destination S_d, through station S_b and S_c without scheduled stops. Train B scheduled on the other line is running from station S_e to station S_f, through station S_c without scheduled stop. The route of train A is 30.4 km long and it consists of continuous uphill and downhill. The slope of uphill is 0.5% and the slope of downhill is 0.6%. It is assumed that train A faces a red signal when approaching block section 10 caused by the delay of train B at junction area. With maximum traction strategy, train A is forced to stop before reaching the end of block section 9, the length of which is 2 km. In other words, v_{res} is equal to 0 and the possible approaching speed v_{gi} ranges from 0 to v_T.

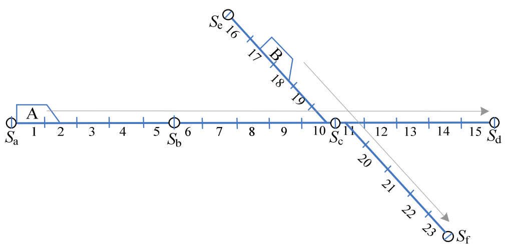

Fig. 3 The railway network for simulations

With the above simulation setup, approaching speed refers to train speed at the time of signal aspects in block section 10 turning from red to green. To analyze the impacts of approaching speed on the time when the train departs from the conflicting area, train movements initialized by different approaching speed are simulated to attain the time for the train departing from the conflicting area. The results are illustrated in table 1. v_T denotes the target speed of train movement. $v(t_a)$ denotes the approaching speed. $\triangle T$ denotes the difference of train run-time in conflicting area with the given approaching speed and that with maximum traction strategy. Positive (negative) number of $\triangle T$ means train run-time with maximum traction strategy is larger (smaller) than that with the given approaching speed.

Table 1 The influences of approaching speed at the time of critical signal aspect upgrades on train run-time in conflicting area

ΔT \ $v(t_a)$ / v_T	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	v_{opt}/v_T
80	0	4	7	8	11	**12**	11	−98	−110									0.63
120	0	4	10	13	15	18	20	**21**	**21**	20	−34	−35	−38					0.63
160	0	10	14	20	24	27	29	31	35	37	38	39	**43**	24	23	21	4	0.75

The results indicate that when the target speeds are 80 km/h, 120km/h and 160 km/h, the optimal approaching speeds are 50km/h, 75km/h and 120km/h, respectively. With the optimal approaching speed, the train is prone to depart from the conflicting area earlier than maximum traction strategy. The delay reduction by optimal approaching strategy reaches 43 seconds when train target speed is 160 km/h. Moreover, at the both sides of optimal approaching speed, the delay reduction of optimal approaching strategy is monotonically increases and decreases, respectively, when the $v(t_a)$ moves from 0 to v_T.

3.3 Golden section search method to determine the optimal approaching speed

According to the results of theoretical analyses and simulation studies, the relationship between the approaching speed and time train departs from conflicting area could be depicted by a single-peak function. Thus, this single-variable problem can be simply solved by classical optimization methods, such as golden section search method. The basic idea of the golden section method [11] is that the solution space is continuously divided into two unequal parts, and at each iteration the parts that contains the optimal solution is chosen until the accuracy of solution is satisfied.

Assuming that the length of solution space is z and the solution space composes of two segments z_1 and z_2, as shown in Fig. 4, the golden section requires that the ratio of the larger one of the two segments to the total length of the interval should be the same as the ratio of the smaller to the larger segment. Therefore, the following equations are obtained,

$$z_1 / z = z_2 / z_1 \tag{10}$$

$$z = z_1 + z_2 \tag{11}$$

By substituting z from (11) into (10), the following equation is obtained:

$$z_1 = 0.618 z_2 \tag{12}$$

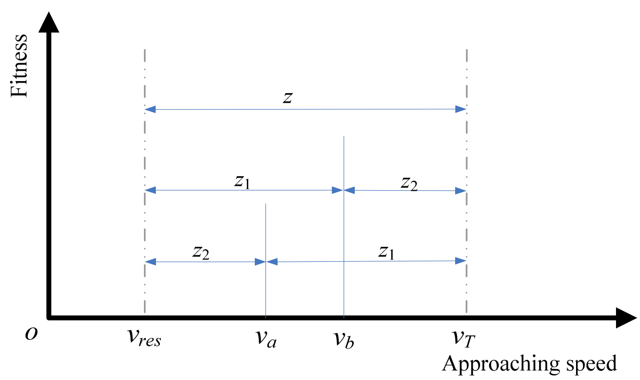

Fig. 4 Golden section search method

As the optimal approaching speed is located between v_{res} and v_T, the searching process with the golden section search method is listed as follows:

1. Take the v_{res} as the approaching speed， simulate train movement and obtain the location where the train recover its speed to the maximum speed, define this location as the end of conflicting area.

2. Two initial approaching speed, v_a and v_b, are placed with the ‘golden ratio’ spacing (i.e. 0.618) from either end of the solution space between v_{res} and v_T. The solution space z will then be reduced to a fraction of 0.618 and $v_a<v_b$ is assumed.

3. Take the v_a and v_b as the approaching speed， simulate train movement and obtain the time when the train departs from the conflicting area $T(v_a)$ and $T(v_b)$, respectively. In case of $T(v_a)$ is lager than $T(v_b)$, v_a replaces v_{res} and the new solution space z_1 becomes (v_a， v_T)； Otherwise， v_b replaces v_T and the new solution space z_1 becomes (v_{res}， v_b)；

4. The process is repeated and the new solution space z_1 is further reduced by the golden ratio until the length of new solution space is smaller than a predefined value. In this paper, the value is defined as 2 km/h, which indicates the error of the obtained optimal approaching speed $v(t_a)=(v_a+v_b)/2$ is less than 1 km/h.

3.4 Advisory train speed profile

Once the optimal approaching speed v_{opt} is identified, the optimal train position at time t_a can be obtained on the speed limit curve. The reason is that the closer to the critical signal post the train position, the earlier the train departs from the conflicting area. Therefore, realizing the optimal approaching speed needs to calculate advisory train speed profile which reaches the point (v_{opt}, s_{opt}) at the time as closer to t_a as possible.

A heuristic algorithm is proposed to achieve the advisory train speed profile. This algorithm is based on the idea that the train is slowed down to v_x and then runs at the speed v_x, which prolongs the train run-time before the conflict area. This action may give way to re-accelerate the train to reach the point (v_{opt}, s_{opt}) without being hindered, as illustrated by figure 2. Consequently, the time when the train reaches the point (v_{opt}, s_{opt}) could be calculated by following equation:

$$t_x = t_0 + t_{dec}(v_0 \to v_x) + t_{acc}(v_x \to v_{opt}) + (s_{opt} - s_0 - s_{dec}(v_0 \to v_x) - s_{acc}(v_x \to v_{opt})) / v_x \tag{13}$$

Where, t_0 denotes the initial time of calculation. $t_{dec}(v_0 \to v_x)$ and $t_{acc}(v_x \to v_{opt})$ denotes the time when the train brakes from v_0 to v_x and the time when the train accelerats from v_x to v_{opt} with maximum traction, respectively. $s_{dec}(v_0 \to v_x)$ and $s_{acc}(v_x \to v_{opt})$ denotes the corresponding distance of braking and motoring, respectively. As the parameters t_0, v_0, v_{opt}, train braking and traction characteristics are known, the time t_x depends on v_x. Therefore, the most important thing in calculating the advisory train speed profile is to identify the variable v_x to minimize the difference between t_x and t_a. The objective function of this problem is as follows:

$$F = |(t_x - t_a) / t_a| \tag{14}$$

In general, t_x is monotonically increased when v_x decreases. Thus, this single-variable problem can be simply solved by golden section search method. By introducing a solution space (0， v_T), the searching process of v_x is listed as follows:

1. Two initial train speed, v_1 and v_2, are placed with the ‘golden ratio’ spacing (i.e. 0.618) from either end of the solution space between 0 and v_T. The solution space will then be reduced to a fraction of 0.618 and $v_1<v_2$ is assumed.

2. Take the v_1 and v_2 as the train speed v_x， simulate train movement and obtain the time t_x that train speed reaches at the optimal approaching speed $F(v_1)$ and $F(v_2)$, respectively. Assume that $F(v_1)$ is smaller than $F(v_2)$, v_2 replaces v_T and the new solution space z_1 becomes (0， v_2)； Otherwise， the new solution space z_1 becomes (v_1， v_T)；

3. The process is repeated and the new solution space z_1 is further reduced by the golden ratio until $F((v_1+v_2)/2)<0.05$ is satisfied.

According to the definition of heuristic method, the advisory train speed profile is attained when the v_x is determined.

4 Case studies

Table 1 illustrates the impacts of approaching speed on the time when the train departs from the conflicting area. The case that the approaching speed is equal to 0 can be regarded as the maximum traction strategy, and the case that the approaching speed is equal to maximum speed can be regarded as the green wave strategy. According to the simulation results in table 1, the optimal approaching strategy is prone to achieve more delay reductions in comparison with the traditional maximum traction strategy and green wave strategy.

The results in table 1 is achieved by the simulations which take different approaching speed and corresponding train location on the speed limit curve as initial train states. However, in real-life train control, it is hard to control the train accurately reach the optimal speed on the speed limit curve. Therefore, the train actual states at t_a may deviate from the optimal states. Consequently the time train departs from the conflicting area may also deviate from the results in table 1.

4.1 Effects of train control strategies on train run-time

Using the same simulation set up in section 3.2, this section simulates the train movement with maximum speed of 160 km/h. The comparison of train speed profile among maximum traction strategy, green wave strategy and optimal approaching strategy is illustrated in figure 5.

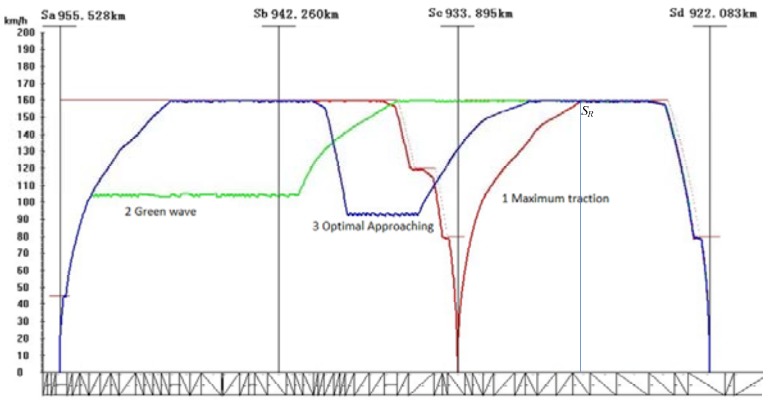

Fig. 5 Train speed-distance curves with three typical control strategies in the simulation

The train speed profile driving with maximum traction strategy is illustrated by curve 1 in figure 5. Because of the red signal aspects caused by service disturbances, the train is forced to stop in front of block section 10. The train resumes its movement after the signal aspect upgrades. The train speed profile driving with green wave strategy is illustrated by curve 2 in figure 5. In this case, the train is decelerated in advance to make the train away from the block section 10 more than one block section at the time of restrictive signal aspects upgrades, so that the train faces only green signal aspects.

The train speed profile driving with optimal approaching strategy is illustrated by curve 3 in figure 5. According to the golden section search, the optimal approaching speed is 119 km/h and the corresponding distance between the train and block section 10 at the time of restrictive signal aspect upgrade is 758 meters. Following the advisory train speed profile attained by the heuristic method proposed in this study, the train reduces its speed to 94 km/h in advance, and then reaccelerates its speed when distance between train A and block section 10 is 1571 meters. With this advisory train speed profile, the train speed is 113 km/h and the train is 759 meters away from block section 10 at the time of restrictive signal aspect upgrade. It is verified that the actual train states obtained by the proposed method may deviate from the theoretical optimal one.

According to the output of the simulator, the train time-distance profile of the aforementioned three train control strategies can be obtained. As showed in figure 6, the time when the train departs from the conflicting area under the maximum traction, green wave and optimal approaching are 12.43 minutes, 12.37 minutes and 11.83minutes, respectively. In other words, the optimal approaching strategy is able to save train run-time up to 36 seconds and 32 seconds in comparison with maximum traction and green wave strategy. As the train was already delayed before entering the conflicting area, the optimal approaching strategy is helpful to recover the train delays as soon as possible and reduce train delays.

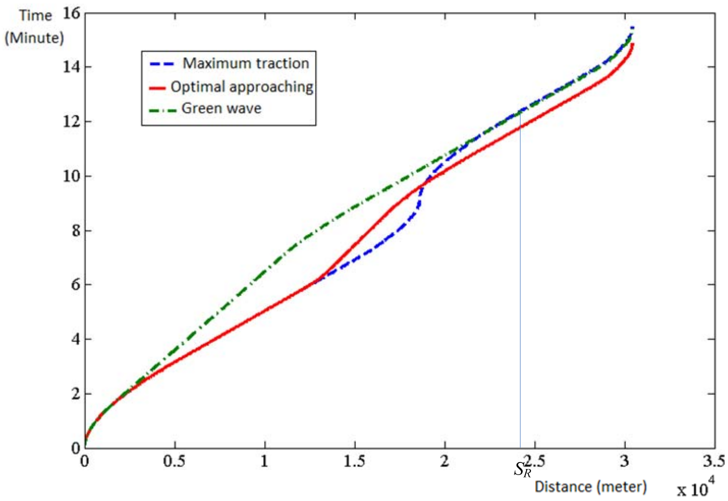

Fig. 6 Train time-distance curves with three typical control strategies in the simulation

4.2 Effects of train control strategies on energy-reduction

Besides the delay reduction, energy consumption is another main concern in railway operation. The comparison of train energy consumption with the three typical control strategies is illustrated by table 2. With maximum traction strategy, the train is forced to stop and therefore results in the loss of energy consumption. With green wave strategy, the train adopts coasting control to slow down the train and therefore save the energy consumption as much as possible. Since the kinetic energy loss caused by braking with optimal approaching strategy is smaller than that with maximum traction strategy, the energy consumption was saved. The energy saving rate is up to 6% in the given case study.

Table 2 Train energy consumption with three typical control strategies in the simulation

Control strategy	Maximum traction	Green wave	Optimal approaching
Energy consumption（kW·h）	797.45	654.70	752.47

In summary, the green wave strategy is able to minimize the energy consumption of train movement while it does not achieve significant delay reduction in comparison with maximum traction strategy. The optimal approaching strategy is able to recover train delays as soon as possible and minimize train delays. At the same time, the energy consumption of optimal approaching strategy is also reduced in comparison with traditional maximum traction strategy. Therefore, the green wave strategy could be adopted to minimize energy consumption when the railway operation is more concern about the energy consumption. The optimal approaching speed could be adopted to recover train delays when the train headway is short and train delay is mostly concerned.

5 Conclusions

This paper presents a time-saving train control method in case of service disturbance at junction area. Golden section search method is adopted to identify the optimal train speed at the expected time of restrictive signal aspect upgrades, which determines the time that the train departs from the conflicting area. A heuristic method is then developed to attain the advisory train speed profile to assist drivers in train control. Simulation results show that the proposed optimal approaching strategy is able to save train run-time in conflicting area and therefore reduce train delays. At the same time, the optimal approaching strategy is also able to save energy consumption compared to the traditional maximum traction strategy.

The proposed optimal approaching strategy is suit for time-saving train control in fixed block signaling system. For moving block signaling system, the optimal train speed at the time of dynamic speed limits caused by disturbances disappearing could also be identified by the proposed golden section search method. However, the continuous changed speed limits curve should be considered when attaining the advisory train speed profile, which is different with the problem in fixed block signaling system. Furthermore, this study assumes that the time when the restrictive signal aspect upgrades is predicted and known. However, there are inevitably errors on estimation of the signal upgrades time in real-life operation. Therefore, further studies are required to investigate the impacts of estimating errors on the effectiveness of the proposed train control method.

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